Breaking the AMSP mould: the increasingly strange case of HETE J1900.1−2455

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Abstract. We present ongoing *Rossi X-ray Timing Explorer* (*RXTE*) monitoring observations of the 377.3 Hz accretion-powered pulsar, HETE J1900−2455. Activity continues in this system more than 3 yr after discovery, at a mean luminosity of 4.4×10^{36} erg s^{-1} (for $d=5$ kpc), although pulsations were present only within the first 70 d. X-ray variability has increased each year, notably with a brief interval of nondetection in 2007, during which the luminosity dropped to below 10^{-3} of the mean level. A deep search of data from the intervals of nondetection in 2005 revealed evidence for extremely weak pulsations at an amplitude of 0.29% rms, a factor of ten less than the largest amplitude seen early in the outburst.

X-ray burst activity continued through 2008, with bursts typically featuring strong radius expansion. Spectral analysis of the most intense burst detected by *RXTE* early in the outburst revealed unusual variations in the inferred photospheric radius, as well as significant deviations from a blackbody. We obtained much better fits instead with a comptonisation model.

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INTRODUCTION

HETE J1900−2455 was discovered following detection of a thermonuclear (type-I) X-ray burst by *HETE-II* [1]. The 377.3 Hz pulsations were detected in a subsequent *RXTE*/PCA observation [2]. Further observations revealed Doppler shifts of the pulse frequency, originating from the orbital motion of the neutron star; the orbital period is 83.25 min [3]. The behaviour of HETE J1900−2455 since then differs remarkably from the other AMSPs. First, the source has been active for >3 yr (to July 2008), roughly an order of magnitude longer than any other AMSP (cf. with [6]), and longer even than the typical outburst intervals in those systems where it is known (e.g. [7]). Second, the amplitude of the pulsations (unusually low to begin with at <3 % rms) decreased systematically on a timescale of ≈ 10 d following several of the thermonuclear bursts observed early in the outburst [8]. Such pulse amplitude variations have not been reported in the other AMSPs in which bursts have been detected (SAX J1808.4−3658 [9] and XTE J1814−314 [10]).

Third, no burst oscillations have been detected — in both SAX J1808.4−3658 and XTE J1814−338, oscillations at the pulsar frequency are present throughout each burst. Fourth, the pulsations in HETE J1900−2455 were present only in the first few months of the outburst, and have not been detected since. While the amplitude of the pulsations in the other AMSPs may vary throughout the outburst, they are always present when detectable, except at the end of the outburst when the source flux has dropped to

(roughly) the background level. For most of its active duration, HETE J1900−2455 has thus been essentially indistinguishable from a faint, persistent, non-pulsing LMXB.

Here we present analyses of the ongoing *RXTE* observations of HETE J1900−2455, including the long-term flux history, as well as the results of a deep pulsation search in the 2005 data during the intervals in which pulsations were not detected in the individual observations. We report the detection of a third burst by *RXTE*/PCA, as well as two bursts by *INTEGRAL* in 2005 and 2006, in addition to those tabled earlier [8]. Finally, we present spectral analysis of the first burst detected by *RXTE*, which exhibited significant devations from a blackbody spectrum.

OBSERVATIONS

Since the first six months of the outburst, during which time observations were more frequent, we made weekly observations of HETE J1900−2455 with *RXTE* each lasting one orbit (typical exposure ≈ 3 ks). We analysed data from the Proportional Counter Array (PCA), which comprises 5 identical proportional counter units (PCU) sensitive to X-ray photons in the range 2-100 keV, and with total effective area ≈ 6500 cm^2 [11]. Spectral resolution is ≈ 18 % at 6 keV; each detected photon is time-tagged to 1μs.

For each observation we extracted the Standard-2 mode data for each PCU and fit the resulting spectra separately in the 2.5–25 keV band using a phenomenological model consisting of an absorbed blackbody plus powerlaw. The resulting reduced-χ^2 ($\chi^2_\nu = \chi^2/n_{\rm DOF}$, where $n_{\rm DOF}$ is the number of degrees of freedom for the fit) values were generally approximately equal to 1, indicating a statistically acceptable fit. We created 122-μs lightcurves covering the same energy range from generic Event mode data, available for all but one of the observations. We adjusted the time bins to the solary system barycenter using the JPL DE200 ephemeris and (for observations through to the end of 2005) corrected for the binary orbit using the parameters of [3].

RESULTS

We measured the 2.5–25 keV flux by integrating the best-fit spectral model over this band; the resulting flux history is shown in Figure 1. The mean flux averaged over 2005–2008 June is $(7.4\pm2.5)\times10^{-10}\ {\rm erg\,cm^{-2}\,s^{-1}}$, corresponding to $4.4\times10^{36}\ {\rm erg\,s^{-1}}$ (assuming $d=5$ kpc, and adopting a bolometric correction to the flux in the 2.5–25 keV band of 1.964), or 2.8% $\dot{M}_{\rm Edd}$. This value is at least two orders of magnitude larger than the time-averaged rate for the other AMSPs (see also [7]). From the beginning of the outburst, we observed significant variations in the flux on timescales of weeks–months. During 2006 these variations appeared to repeat on a timescale of ≈ 125 d, but this was not the case before and after. The variability of the source has increased with each year of activity, with the possible exception of 2008. The greatest variability in 2007 was notably accompanied by a brief transition to quiescence; a dramatic drop in flux measured with *RXTE* in May was followed by a non-detection by *Swift* [12, 13], only to recover a few days later [14]. The upper limit on the luminosity when HETE J1900−2455 was undetected by *Swift* was $\sim 5\times10^{32}\ {\rm erg\,s^{-1}}$; a detailed analysis of the quiescent interval

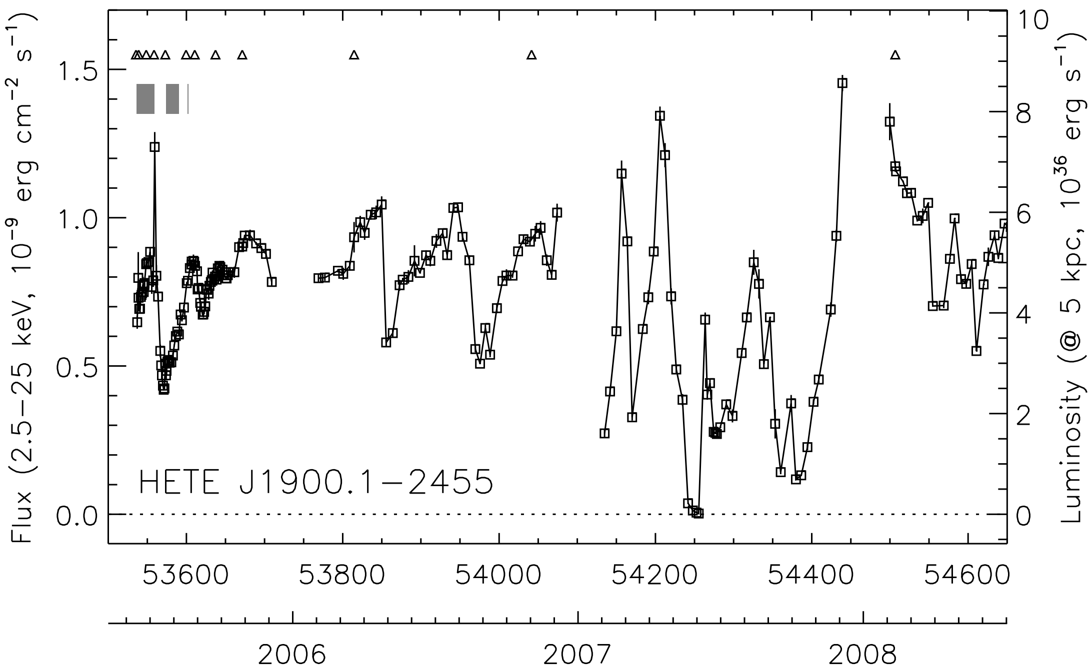

FIGURE 1. Long term flux history of HETE J1900−2455, as measured by *RXTE*. The open squares are the fluxes measured from spectral fits of PCA observations, averaged over the active PCUs (excluding PCU #1). The open triangles show the times of bursts detected by various instruments. The grey regions indicate the intervals during which pulsations were detected. We were unable to observe for a 60-d period at the turn of each calendar year, when the source was too close to the sun.

and subsequent recovery will be presented in a subsequent paper.

In the monitoring observations to date we have also observed significant variations in the X-ray colors of HETE J1900−2455. These variations in some cases are associated with short-duration (of order hours) flaring in the source; one example is the bright flare around MJD 53559 (Fig. 1). Such flares and related color variations have not been observed in any of the other AMSPs; those sources exhibit a color-color diagram typically with a single locus, without the large variations seen in HETE J1900−2455.

Deep searches for pulsations

Pulsations have not been detected in the individual *RXTE* observations of HETE J1900−2455 since MJD 53602 [8]. The pulsations became undetectable in two earlier intervals, the first following a large flare early in the outburst [3]. The pulsations only returned following the thermonuclear burst that was detected by the PCA on 2005 July 21 (MJD 53572). We performed a deep search for pulsations in the eight observations which were performed between MJD 53561 and 53571 (totalling 31.3 ks). For each observation, we performed a FFT of the orbit- and barycentre-corrected 122-μs binned, 2.5–25 keV lightcurve, and added the powers in the bin spanning the previously determined pulse frequency [3]. We set our detection threshold corresponding to 3σ

confidence, equivalent to a summed (Leahy-normalised) power of 36.2. The total power detected in the bin covering the pulse frequency was just 9.48. The corresponding upper limit on the signal power in the summed bin is 21.3, leading to an upper limit (at 3σ confidence) on the fractional pulse amplitude of 0.31% rms.

Pulsations were detected in just one of five observations between MJD 53588 and 53600. Since the total exposure during this interval was less than in the previous nondetection interval, we cannot likely improve on the limits determined above. Instead, we performed a deep search for pulsations from the last detection (on MJD 53602) through to the end of 2005. We summed FFTs from 41 observations totalling 136.7 ks between MJD 53608–53709. The 3σ threshold for a detection in a single bin of the summed power spectrum is a Leahy power of 122; in the bin corresponding to the previously measured pulse frequency of HETE J1900−2455 we measured a power of 139, confirming a detection. The corresponding amplitude is 0.29% rms, which is just below the upper limit determined during the previous interval of non-detection. We also searched each FFT individually, taking into account the number of trials, but found no detections.

The X-ray bursts

Bursts from HETE J1900−2455 have been detected by *RXTE*/PCA and ASM, *Swift*, and *INTEGRAL* (Table 1). Although the majority of bursts were detected early in the outburst, this is likely due to the increased observational duty cycle at that time; we expect that bursting activity has continued throughout the outburst at approximately the same level, commensurate with the relatively steady inferred accretion rate.

The peak flux of the first burst detected by *HETE-II*, assuming it reached the Eddington limit for a pure-He atmosphere, indicated a distance of 5 kpc [15]; analysis of all five bursts detected by *HETE-II* between 2005 June–July indicated a reduced distance of 4 kpc [16]. The first two bursts detected by *RXTE*/PCA had similar peak fluxes to those detected earlier, and time-resolved spectral analysis confirmed the identification as photospheric radius-expansion bursts [17]. The third burst detected by *RXTE*/PCA on 2008 February 10 was very similar to the second, with essentially identical peak flux, and fluence around 10% smaller. The corresponding distance (assuming that the bursts reach the Eddington limit for pure-He material) is 4.8 ± 0.5 kpc. As for the previous bursts detected by *RXTE*/PCA, we searched this burst for oscillations at the pulse frequency, but found none.

We also examined the spectral evolution of all three bursts detected by *RXTE*. We fitted the burst spectra (using the pre-burst emission as background, which includes the persistent flux and the instrumental background) with a blackbody affected by neutral absorption, following the usual approach (e.g. [17]). All three bursts exhibited radius expansion, indicated by a local maximum in the blackbody radius near the flux maximum, coincident with a local minimum in the blackbody temperature. The second and third bursts, on 2006 March 20 and 2008 February 10, exhibited similar spectral variation, both with a pronounced double peak in the (extrapolated) bolometric flux (Figure 1, right panels). Although unusual, such double peaks are not unprecedented (e.g. [17]). The first burst, however, was much more energetic, and exhibited quite

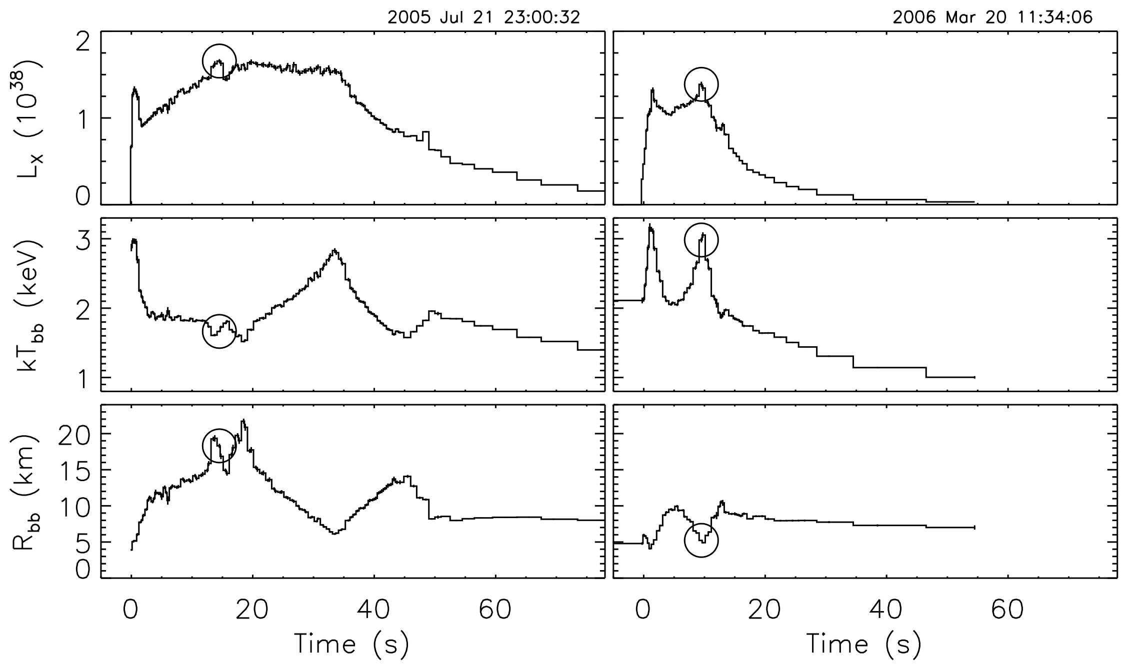

FIGURE 2. Two of the three X-ray bursts observed from HETE J1900−2455 by *RXTE*/PCA, on 2005 July 21 (*left panels*) and 2006 March 20 (*right panels*). *Top panels* The estimated luminosity assuming isotropic emission from a source at $d = 5$ kpc. The circle marks the point at which the maximum flux was reached. *Middle panels* The blackbody temperature and *Bottom panels* The blackbody radius (at $d = 5$ kpc). Error bars indicate the 1σ uncertainties.

bizarre spectral evolution. A rapid rise in flux initially ended with a brief precursor (lasting 2 s), followed by a more gradual rise to a peak at around 15 s after the burst start (Figure 1, left panels). During this rise the blackbody radius also rose steadily, but then more sharply near the peak to give two local peaks in the radius, separated by 5 s. Following these peaks the radius decreased again, but reached a third local maximum at around 45 s. By this time the burst flux had dropped to approximately one-half the maximum. After this final peak the radius was approximately constant through the remaining decay. The blackbody temperature was roughly anticorrelated with the radius until the final decay stage.

The unusual spectral evolution prompted a closer examination of the time-resolved spectra. Throughout the first 35 s of the burst, the χ^2_ν values were in the range 1–3, but during the third radius maximum the χ^2_ν also rose, to a maximum of greater than 9.6. Examination of the individual spectra revealed a deficit of photons between 7–9 keV, suggestive of a photoionisation feature from neutral or ionised Fe, as observed in the superburst from 4U 1820−30 [18]. Using the spectral model fitted to those data for the HETE J1900.1−2455 burst, we could not obtain an acceptable fit, likely due to the lack of strong Fe Kα line emission which is expected to accompany the edge for mildly ionised disk material. Instead, the spectra throughout the burst were well-fit with a comptonisation model, `comptt` in XSPEC [19], with mean χ^2_ν values over the burst of 1.47, although with a maximum of 3.84. The spectral fit parameters for this model show significant evolution throughout the burst (Figure 3). In particular, around the time when

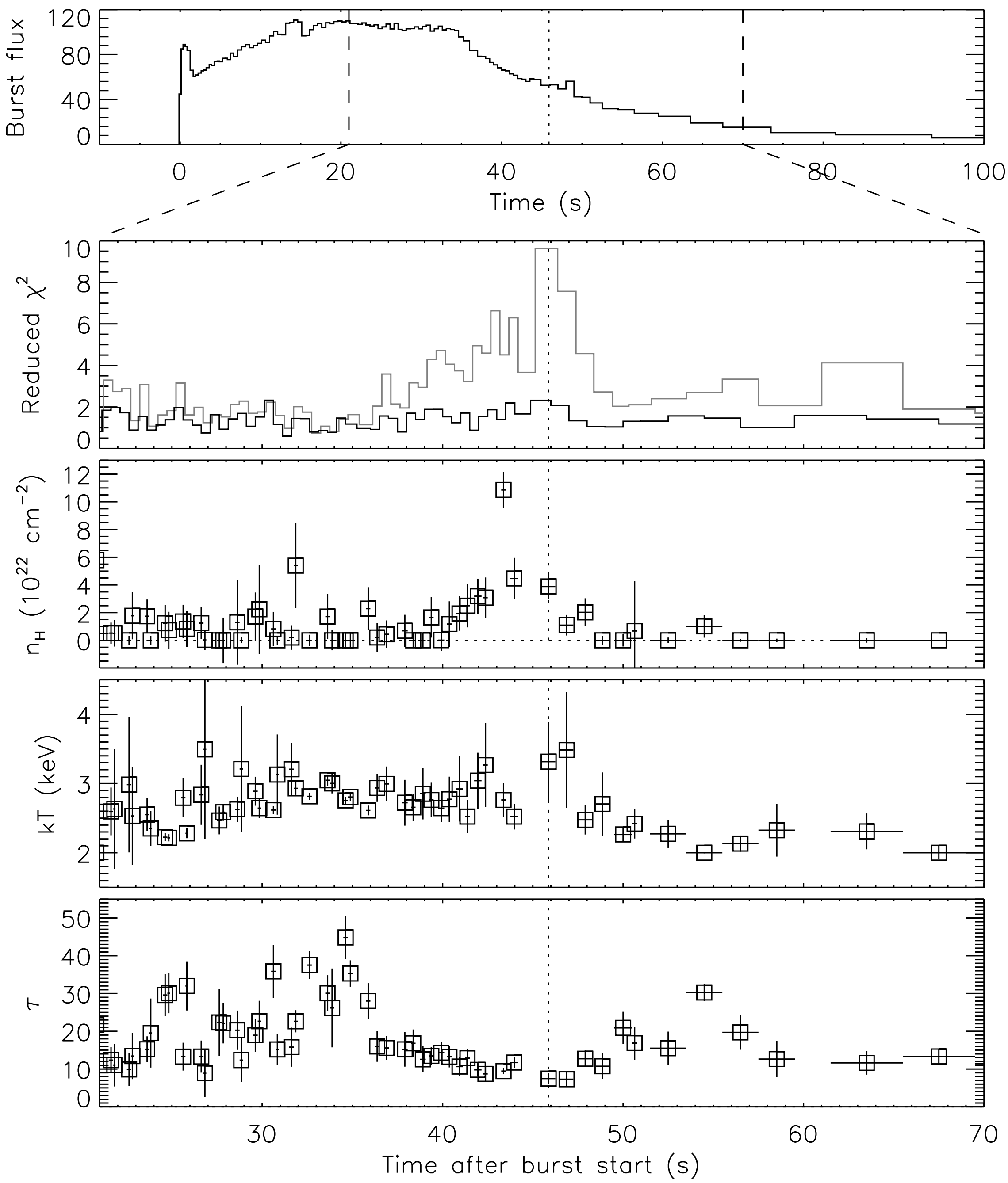

FIGURE 3. Spectral evolution throughout the burst from HETE J1900−2455 on 2005 July 21, according to an absorbed comptonisation model. The top panel shows the burst flux (bolometric, estimated from the initial blackbody fits) in units of 10^{-9} erg cm^{-2} s^{-1}. The second panel compares the reduced-χ^2 (χ^2_ν) values versus the blackbody (*grey histogram*) and comptonisation (*black histogram*) components during the second half of the burst peak and the initial decay. Note the maximum χ^2_ν of 9.6 for the blackbody fit at 45.5 s after the burst start; this time is indicated as the vertical dotted line in each panel. The third panel shows the fitted neutral column density for the comptonisation model fit; the fourth and fifth panels show the scattering temperature kT and optical depth τ, respectively. Error bars indicate the 1σ uncertainties.

TABLE 1. Type-I X-ray bursts observed from HETE J1900−2455

Start time (UT)	(MJD)	Instrument	Ref.
2005 Jun 14 11:22	53535.47361	*HETE-II*	[1, 15, 16]
2005 Jun 17 21:49:10	53538.90914	*HETE-II*	[16]
2005 Jun 27 13:54:10	53548.57928	*HETE-II*	[16]
2005 Jul 7 13:09:22	53558.54891	*HETE-II*	[16]
2005 Jul 21 23:00:32	53572.95871	*RXTE*/PCA & *HETE-II*	[8] [16]
2005 Aug 17 12:19:58	53599.51387	*Swift**	
2005 Aug 28 15:09:37	53610.63167	*Swift**	
2005 Sep 24 04:47:10	53637.19941	*RXTE*/ASM†	
2005 Oct 28 10:25:30	53671.43438	*INTEGRAL***	
2006 Mar 20 11:34:06	53814.48202	*RXTE*/PCA	[8]
2006 Nov 2 13:32:22	54041.56414	*INTEGRAL***	
2008 Feb 10 20:32:51	54506.85615	*RXTE*/PCA	

* BAT triggers #150823, 152451; C. Markwardt, pers. comm. (2005)
† R. Remillard, pers. comm. (2005)
** Events 2693/0, 3529/0 at http://wydra.ncac.torun.pl/∼jubork/ibas

the χ^2_ν for the blackbody fit reached a maximum, we find evidence of enhanced neutral absorption, and relatively low values of $\tau = 7$–16. We are not aware of any previous analyses of burst spectra with such a model.

SUMMARY & FUTURE PROSPECTS

HETE J1900−2455 continues to reveal surprising behaviour. The "failed" transition to quiescence in 2007, as well as the X-ray intensity and color variability, further extends the range of AMSP phenomenology. We have also found unusual burst spectral shape and variations in the first burst detected by *RXTE*. Significant deviations from the usual blackbody model could not be modelled using a reflection spectrum, but instead were fit with an absorbed comptonisation model. During the stage of the burst in which we detected the most significant devations from a blackbody spectrum, we found evidence of significantly enhanced neutral absorption, as well as a lower-than-usual optical depth for scattering τ. It is not clear how (if at all) the unusual spectral shape and variations may be related to the atypical behaviour inferred for the photospheric radius throughout the expansion. A preliminary study of spectra from almost 1200 bursts observed by *RXTE* [17] indicates that deviations from a blackbody model can be most commonly explained by comptonisation, both in radius-expansion and non-radius expansion bursts.

However, it is the behaviour of the pulsations early in the outburst that is of most interest. The accumulated exposure from the last detection through to the end of 2005 allowed us to detect a weak signal with amplitude of just 0.29% rms. At just below the upper limit obtained for the first interval of nondetection, we cannot exclude the presence of pulsations at this level also in that interval. Rather than being absent altogether, the

pulsations appear to be present but at an amplitude of around 10% of the maximum reached earlier in the outburst. For the observations from 2006 onwards, the accumulated error in the orbital ephemeris necessitates an acceleration search for pulsations. This search is currently under way.

The lack of pulsations in the broader class of LMXBs (which are mostly accreting above the rates typical for the AMSPs) has been suggested to arise from "burial" of the magnetic field by the accreted material. A combination of properties in HETE J1900−2455 (unusually low magnetic field strength, sustained accretion) perhaps makes it uniquely susceptible to burial compared to the other AMSP systems (see also Cumming, this volume). The continued presence of pulsations at $\approx 10\%$ of the peak amplitude detected earlier in 2005 suggests that the field may not be completely buried, but reduced by a commensurate amount.

If such mechanisms prove plausible to explain the properties of the pulsations in HETE J1900−2455, possibly including the response to the thermonuclear bursts, the future behaviour — particularly episodes of very low accretion rate, as was observed in 2007 — may provide direct tests of the burial scenario.

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